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T. Kennedy-Bowdoin, E.A. Silver, B.A. Martini, W.L. Pickles

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T. Kennedy-Bowdoin[1], E. A. Silver[1], B. A. Martini[2], W. L. Pickles[3]

[1] University of California at Santa Cruz
[2] HyVista Corporation, Sydney, Australia
[3] Lawrence Livermore National Labs

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ABSTRACT

In an ongoing project to relate surface hydrothermal alteration to structurally controlled geothermal aquifers, we mapped a 16 km swath of the eastern front of the Stillwater Range using Hyperspectral fault and mineral mapping techniques. The Dixie Valley Fault system produces a large fractured aquifer heating Pleistocene aged groundwater to a temperature of 285° C at 5-6 km. Periodically over the last several thousand years, seismic events have pushed these heated fluids to the surface, leaving a rich history of hydrothermal alteration in the Stillwater Mountains. At Dixie Hot Springs, the potentiometric surface of the aquifer intersects the surface, and 75° C waters flow into the valley. We find a high concentration of alunite, kaolinite, and dickite on the exposed fault surface directly adjacent to a series of active fumaroles on the range front fault. This assemblage of minerals implies interaction with water in excess of 200° C. Field spectra support the location of the high temperature mineralization. Fault mapping using a Digital Elevation Model in combination with mineral lineation and field studies shows that complex fault interactions in this region are improving permeability in the region leading to unconfined fluid flow to the surface. Seismic studies conducted 10 km to the south of Dixie Meadows show that the range front fault dips 25-30° to the southeast (Abbott et al., 2001). At Dixie Meadows, the fault dips 35° to the southeast, demonstrating that this region is part of the low angle normal fault system that produced the Dixie Valley Earthquake in 1954 (M=6.8). We conclude that this unusually low angle faulting may have been accommodated by the presence of heated fluids, increasing pore pressure within the fault zone. We also find that younger synthetic faulting is occurring at more typical high angles. In an effort to present these findings visually, we created a cross-section, illustrating our interpretation of the subsurface structure and the hypothesized locations of increased permeability. The success of these methods at Dixie Meadows will greatly improve our understanding of other Basin and Range geothermal systems.

Introduction

As oil prices continue to skyrocket, development of alternative energy sources becomes increasingly important. Geothermal power is a cost effective alternative to fossil fuel that could power much of the western United States. Extensional tectonics in the

Basin and Range province provide elevated heat flow and fractured rock permeability. Pleistocene lake waters trapped within these fractured zones provide a vast region of potentially productive geothermal aquifers. Most of the clearly productive geothermal systems in this region have been developed, and advanced methods for locating previously hidden resources need to be created.

Hydrothermal alteration mineralogy can tell us a lot about the history of a geothermal system and help us evaluate its economic potential. Periodically seismic events push heated fluids to the surface causing hydrothermal alteration. Surface mineralogy can determine the temperature, pressure, and chemistry of the fluids, as well as their distribution. Traditional field mapping of hydrothermal mineral alteration can be tedious and costly. Hyperspectral imaging has proven to be a very effective method in mapping these minerals. Martini (2002) used this technique with HyMAP and Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) hyperspectral data to gain an understanding of the local tectonic, hydrothermal, biological, and volcanic systems in Long Valley Caldera, and Crowley and Zimbelman (1997) used AVIRIS to map alteration on Mt. Rainier.

In an effort to apply these techniques to the realm of geothermal prospecting, the consortium of the University of California at Santa Cruz (UCSC), Lawrence Livermore National Labs (LLNL), the University of Nevada at Reno (UNR), and the University of Utah (UU) collected a HyMAP hyperspectral dataset at Dixie Meadows, in August of 2002 (see figure 1). This area is an ideal location for this study because of its close proximity to the largest geothermal field in Nevada (the Dixie Valley geothermal field). HyMap uses 126 spectral bands to collect data in the visible through the short wave infrared wavelengths. The spectral sampling in the range between the wavelengths of 2.0 and 2.5 μm is tailored to the needs of geologic mineral identification. The airborne high-resolution hyperspectral imagery has a spatial resolution of about 3 meters.

This portion of the basin and range is also geologically interesting for many reasons. The Dixie Valley Fault produced one of the only recorded large earthquakes on a low angle normal fault (Abbott et al., 2001). Activity on faults with a dip of less than 45 degrees is a highly debated subject. Andersonian theory of faulting would not predict such a fault mechanism (Anderson, 1942), however, several researchers (Abers et. al., 1997, Abbott et al., 2001, Johnson and Loy, 1992) have shown that a significant portion of shallow crustal extension is accommodated in this manner. The Dixie Fault system is an interesting field area to study these events and determine what properties of the system might enable this type of faulting.

Methods

The Dixie Meadows dataset consists of eighteen North-South trending flightlines. HyVista Corporation conducted post-processing to atmospherically correct the data that were then made available to Lawrence Livermore National Laboratories in November of 2002. Simultaneously, UCSC began its analysis of the data using Research Systems Incorporated (RSI) Environment for Visualizing Images (ENVI™) software.

Initially, the large data set was subset into smaller areas of interest along the range front. Two algorithms included with ENVI software were used to reduce the number of mixed pixels within the subsets, Minimum Noise Fraction (MNF) and Pixel Purity Index (PPI). MNF is an algorithm designed to allow the user to separate out the noise inherent in a data set, and determine what part of the dataset is spectrally useful. PPI is an algorithm used to find the pixels within the dataset that are spectrally distinct. Endmembers were selected from the remaining pixels. Finally, the distribution of these endmembers were mapped using mixture tuned matched filtering (MTMF). These maps were field checked using an Analytical Spectral Devices (ASD) Field Spec Pro field spectrometer (see figure 2).

The 3D SurfaceView function allows the user to view a Digital Elevation Model (DEM) with georectified imagery draped over it. Correlation between mineral alteration lineations and changes in slope can be assumed to be fault related. Detailed fault maps were made using these methods. Traditional field methods were used to check the locations of mapped faults and determine strike and dip and relative motion between blocks. Linear trends in vegetation were also used in conjunction with other evidence to locate faults. This method works well in arid regions where surface water must come up along faults from deep aquifers to allow vigorous plant growth.

Results

After large-scale mineral mapping of the 16 km imaged range front, one subset proved to show a high concentration of high-temperature alteration minerals. The majority of our research is focused on this region (see figure 4). At least three zones of alteration can be distinguished: acidic alteration (high temperature) of Tertiary tuffs, alkaline alteration of Tertiary tuffs, and intermediate alteration of Triassic meta-sedimentary rocks (see figure 3).

Acidic alteration is common in regions with fluid temperatures in the range of 100-350° C, and results in a characteristic suite of alteration minerals. Halloysite, kaolinite, alunite, quartz, and dickite are all minerals within this group that were mapped in the acidic alteration zone. Parent rock has little effect on the resulting acidic alteration minerals. Alkaline alteration forms in Ca- and Na-rich fluids, and at moderate temperatures zeolites commonly form. Intermediate alteration is typical when fluids are rich in Ca-Mg, and K, and results in illite/smectite mineralogy at moderate temperatures, and chlorite-epidote mineralogy at higher temperatures (Inoue, 1995). In figure 3, the distributions of these minerals were used to outline zones of alteration.

Our field observations of structures in this region show that the Dixie Valley Fault dips 35 degrees to the southeast at Dixie Meadows. This extends the region of active low angle normal faulting on this fault at least 10 km to the north of the Abbott et al. (2001) study.

We measured 75° C waters at Dixie Hot Springs, where water reaches the surface along a synthetic fault. At the Dixie Meadows fumaroles, we measured 94° C ground temperatures and observed active precipitation of sulfur minerals.

Discussion

The zone of acidic alteration is directly adjacent to active fumaroles that are presently precipitating acidic alteration minerals, indicating that geothermally heated water is boiling near the surface (Inoue, 1995). This acidic alteration occurs at the intersection of two faults, indicating that the permeability of the fault system is increased in this region. The zones of intermediate/alkaline alteration may access different fluids or alteration may occur over longer time scales. The fault conduits may penetrate to a different depth in the aquifer, explaining the difference in chemistry and temperature of the alteration. The faults could also be less dilated, allowing slower movement of fluids and greater cooling before reaching the surface.

The combination of all of the data acquired in this study and the cross-section constructed by Abbot et al. (2001) allows us to interpret the subsurface geology and structure at Dixie Meadows. Figure 5 illustrates that the source of the fluids at Dixie Hot Springs and the alteration and fumarolic activity at the range front is a 2 to 3 km deep geothermally heated, fractured rock aquifer.

Conclusions and Future Work

In the Dixie Meadows field area, range front faulting is occurring on low angle normal faults. The presence of hydrothermal fluids along the Dixie Valley Fault correlates well with active portions of the fault. Hyperspectral mineral mapping resulted in an accurate map of modern high temperature alteration minerals and faulting. Using these techniques, we are able to pinpoint a geothermally heated permeable aquifer that could be developed into a productive geothermal field.

These methods will greatly facilitate the exploration of geothermal resources in the future. We are presently collaborating with Presco Energy LLC at the Humboldt/Rye Patch geothermal system. It is our hope that this type of research will be incorporated into the geothermal prospecting industry.

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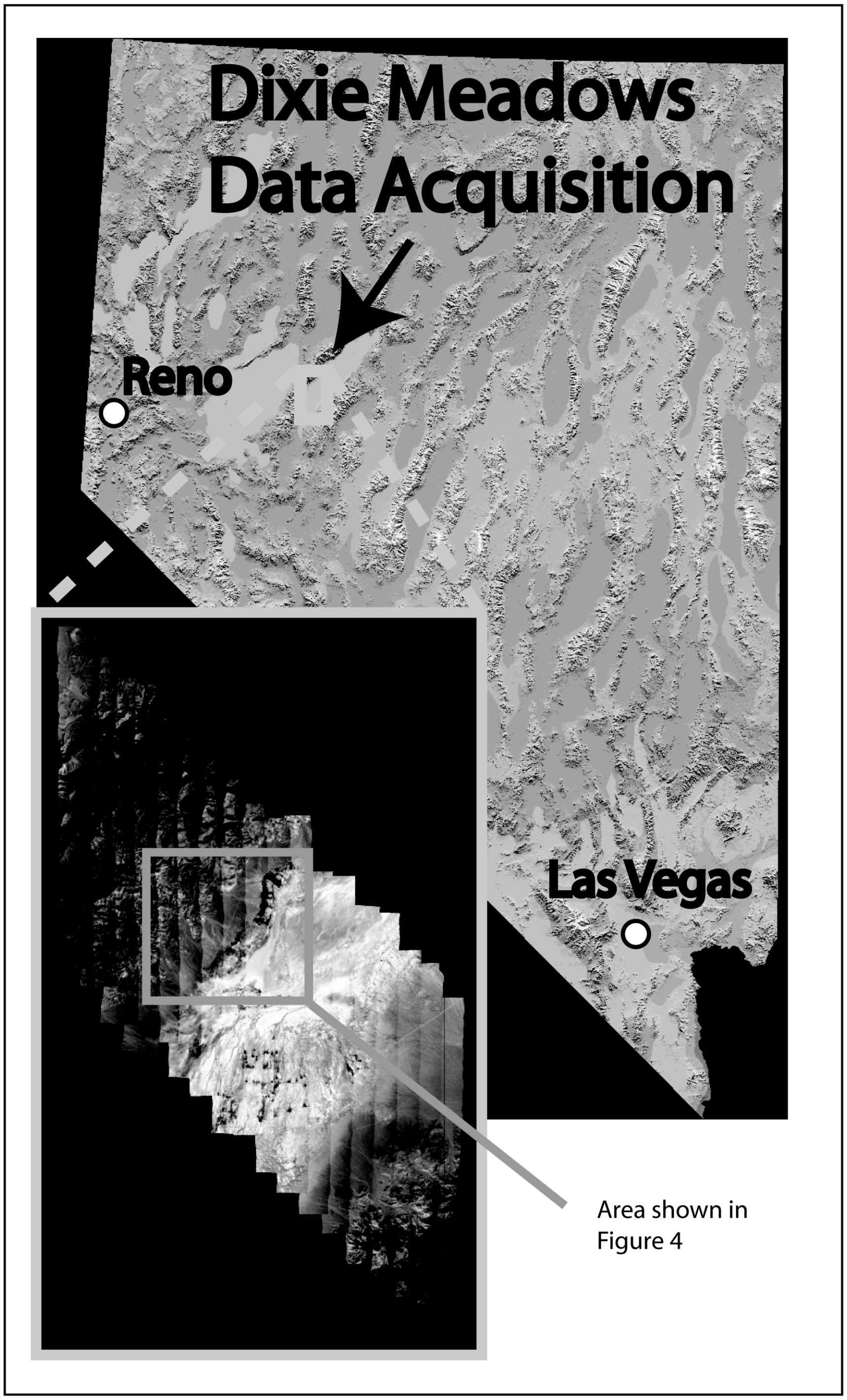

Figure 1. Location of Dixie Meadows HyMap Data acquired in 2002.

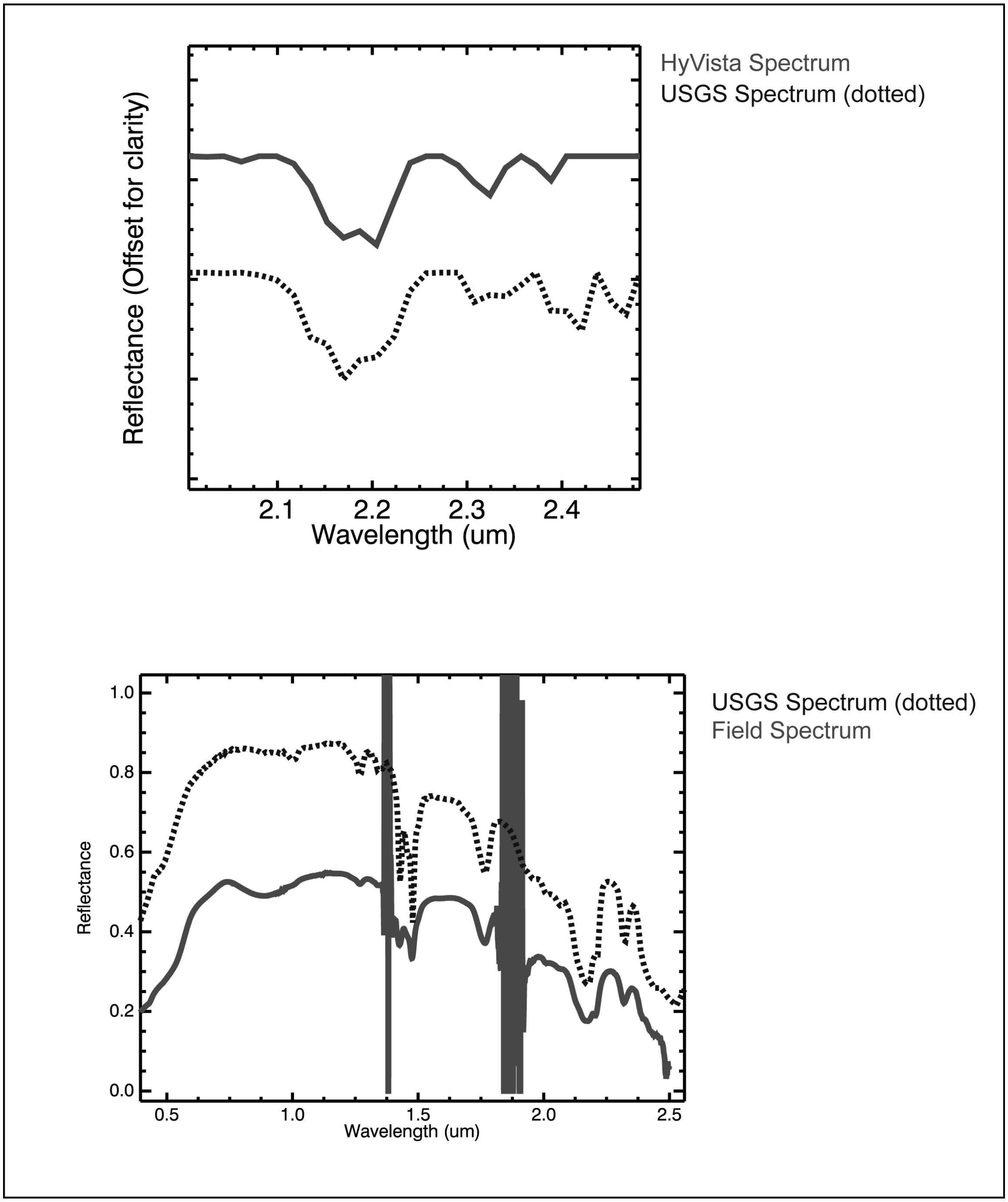

Figure 2. The first plot compares the spectrum of a pixel extracted from the HyMap data to the USGS lab spectrum for alunite. The differences are the result of mixing of materials within the pixel. The second plot compares the USGS spectrum to an averaged field spectrum taken at the location of the pixel shown in the first plot. Please note that the first plot and the second plot cover a different range of the spectrum.

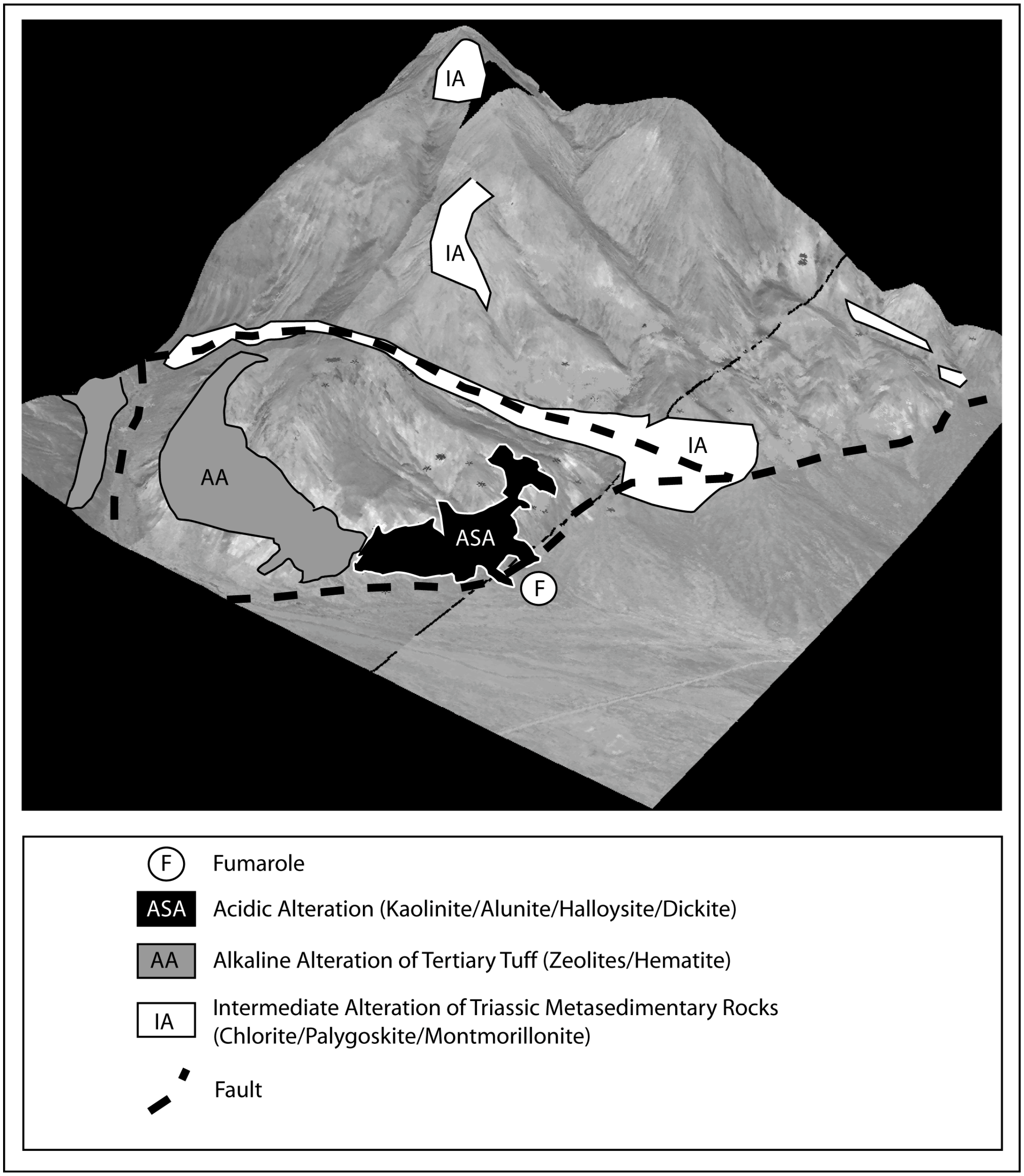

Figure 3. The three zones of alteration described in the text are superimposed upon the 3D surface view. This view is looking to the northwest.

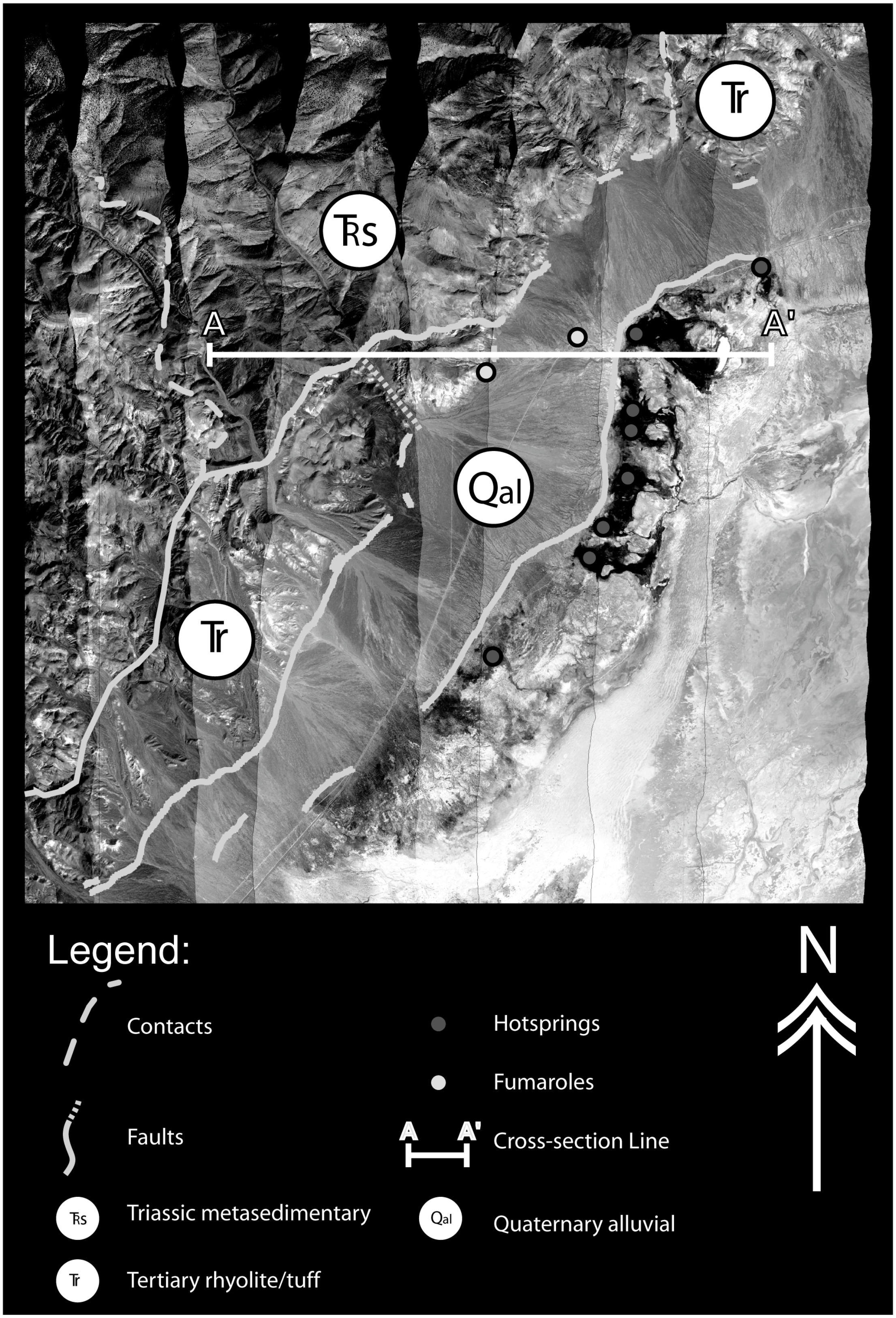

Figure 4. Important faults and contacts mapped using the HyMap data and field methods. Note that the cross-section line (figure 5) is shown in map view.

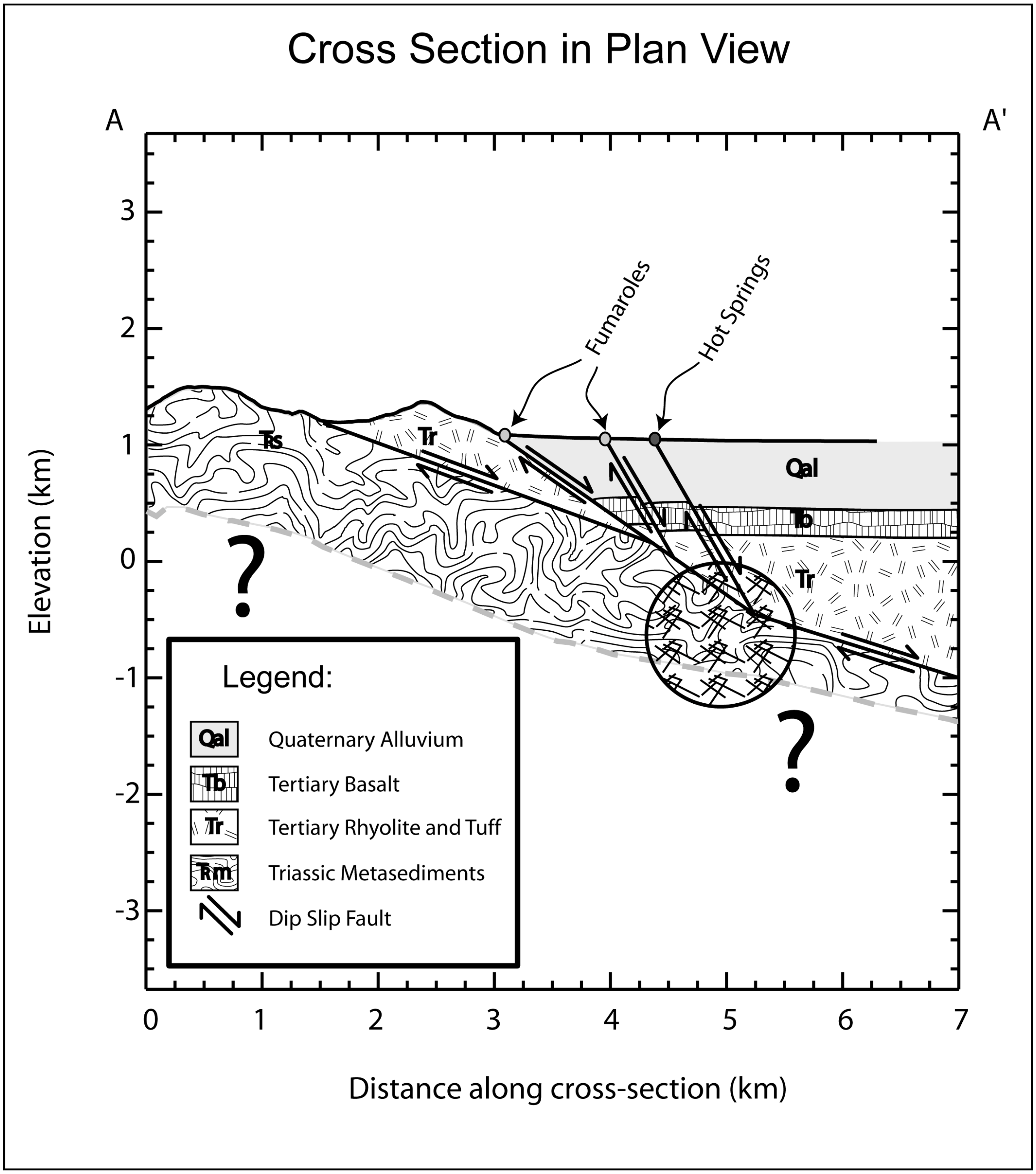

Figure 5. Faults grow progressively steeper to the east; modern faulting is forming at typical normal fault angles. The hatched area depicts the proposed location of the high fracture permeability induced by complex fault interactions. The question marks indicate that the location of the Humboldt complex of intrusive rocks is unknown.